

COMBINED AERODYNAMIC AND STRUCTURAL OPTIMIZATION OF A HIGH-SPEED CIVIL TRANSPORT WING

Peter J. Röhl^{*}, Dimitri N. Mavris^{**}, Daniel P. Schrage[†]

School of Aerospace Engineering, Georgia Institute of Technology
Atlanta, GA 30332-0150

Abstract

A combined procedure for the aerodynamic and structural optimization of a High-Speed Civil Transport wing is presented. Primary goal of the procedure is the determination of the jig shape of the wing necessary so that it deforms into its optimum shape in cruise flight. The wing twist and camber distribution is optimized for the cruise condition using WINGDES, a code based on a linearized potential flow solution for zero-thickness lifting surfaces. The structural design is decomposed into three levels. The top level uses the FLOPS aircraft synthesis program to generate preliminary weights, mission, and performance information. The optimization criterion is productivity expressed by a productivity index for the specified mission. The second level of the system performs a finite-element based structural optimization of the wing box with the help of the ASTROS structural optimization tool. The wing structure is sized subject to strength, buckling, and aeroelastic constraints. The buckling constraint information is supplied by the third level where a detailed buckling optimization of individual skin cover panels is performed. The Georgia Tech HSCT baseline aircraft is presented and the resulting optimum wing structure, cruise and jig shapes are explained in detail.

Nomenclature

a_{ij}	shape function coefficient
PI	productivity index
t	panel thickness
V_b	block speed
W_e	empty weight
W_f	fuel weight
W_p	payload
ξ	nondimensional chordwise coordinate
η	nondimensional spanwise coordinate

1. Introduction

Barriers that have traditionally existed between the different disciplinary entities involved in aircraft design are being recognized more and more as obstacles for a truly "Multi-Disciplinary" system approach to the design problem. While there are fully integrated multidisciplinary tools at the conceptual level (FLOPS¹, ACSYNT² etc.), a "throw-it-over-the-wall" mentality is still prevalent at the

preliminary level where disciplinary groups work mostly by themselves. For a highly-coupled system like the proposed High-Speed Civil Transport (HSCT) where the margin between economic success and failure will be very small, this approach is completely unacceptable and new methodologies for system design and optimization will be crucial.

At the same time, the methodology of multidisciplinary design and optimization is evolving into a new engineering discipline that seems most suitable to address this type of problem³. In the light of this, the Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology is heavily involved in the development, enhancement, and implementation of the technologies of Concurrent Engineering (CE) and Integrated Product and Process Development (IPPD)^{4,5,6}. One of the focal points of these ongoing efforts is the development of a second generation supersonic transport aircraft. A multilevel design procedure has been developed that addresses the wing structural design which is decomposed from the system level (aircraft) via the subsystem level (wing) down to the component level (skin cover panel)^{7,8,9}.

One area that still needed further attention was the integration of structural and aerodynamic wing design. The present paper attempts to lay the groundwork for a combined truly multidisciplinary aerodynamic and structural wing design procedure, although it is realized that this effort can merely be regarded as a first step in that direction. So far, the design procedure is still biased towards the structural side since that is the origin of the effort, but it can be viewed as a basis for combined aerodynamic and structural design.

2. Combined Structural and Aerodynamic Optimization Procedure

2.1. Structural Optimization Through Multilevel Decomposition

The wing structural design problem is decomposed into three levels in a hierarchical structure (Fig. 1). At the top level, a general aircraft sizing and performance code sizes the aircraft for the specified mission based on statistical, empirical, and analytical methods. At the middle level the actual structural layout of the wing takes place based on a relatively crude finite element analysis. On the third level individual skin cover panels which are modeled as membrane elements with a smeared thickness at the second level are sized for buckling as stiffened panels.

^{*} Graduate Research Assistant, Student Member AIAA

^{**} Research Engineer, Member AIAA

[†] Professor, Aerospace Engineering, Member AIAA

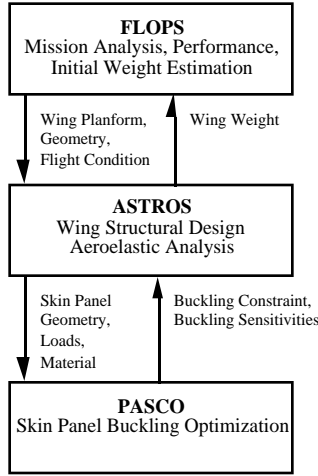


Fig. 1: Multilevel Decomposition of the Wing Design Problem

2.1.1. Analysis and Design Modules

The top level uses the code FLOPS (Flight Optimization System) developed by NASA Langley which has been modified for this application and for its integration into the multilevel scheme. FLOPS is a multidisciplinary system of computer programs for conceptual and preliminary design and evaluation of advanced aircraft concepts. It consists of nine primary modules for weights, aerodynamics, engine cycle analysis, propulsion data scaling and interpolation, mission performance, takeoff and landing, noise footprint calculation, cost analysis, and program control. The weights module uses statistical / empirical equations to predict the weight of each item in a group weight statement and also calculates centers of gravity and moments of inertia. The aerodynamics module provides drag polars for performance calculations. The engine cycle analysis module provides the capability to internally generate an engine deck consisting of thrust and fuel flow data at a variety of Mach-altitude conditions. The mission performance module uses the calculated weights, aerodynamics, and propulsion data to calculate performance and the fuel balance. Through the program control module, FLOPS may be used to analyze a point design, parametrically vary certain design variables, or optimize a configuration with respect to these design variables. Possible objective functions include gross weight, range, fuel weight, and combinations thereof. The configuration design variables include wing area, wing sweep, wing aspect ratio, wing taper ratio, wing thickness to chord ratio, and thrust. The performance design variables are cruise Mach number and maximum cruise altitude. The engine cycle design variables are the design point turbine entry temperature, the maximum turbine entry temperature, the fan pressure ratio, the overall pressure ratio, and the bypass ratio for turbofan and turbine bypass engines.

The Productivity Index PI, defined as the ratio of aircraft productivity to the sum of fuel and empty weight,

$$PI = \frac{PL \cdot V_B}{W_e + W_f}, \quad (1)$$

has been selected as a measure of aircraft performance and has been programmed as a possible objective function. At a time when economic data for a supersonic transport aircraft are sketchy at best, the productivity index offers a measure of comparing different configurations by normalizing aircraft productivity (block speed times payload) with respect to an indicator of the cost involved in achieving this productivity. The denominator captures a part of both the operating costs (through the fuel weight which directly translates into fuel cost) and the acquisition cost which is usually calculated as a function of aircraft empty weight.

The structural optimization level uses the ASTROS¹⁰ (Automated Structural Optimization System) code to design a minimum weight wing subject to a large number of stress, strain, displacement, and flutter constraints. ASTROS is a multidisciplinary analysis and design tool most suitable for the design of aerospace structures. It was developed for and by the Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, and has been continuously upgraded. The latest version being used now is Version 11. It combines finite-element-based structural analysis, aerodynamic and aeroelastic analysis with mathematical optimization algorithms in order to design a minimum weight structure meeting a variety of different types of constraints. The engineering analysis capabilities include both static and dynamic structural analyses (transient and steady-state) and static and dynamic aeroelastic capabilities. Design constraints include stress, strain, displacement, frequency, flutter, and aerodynamic constraints. Data storage and manipulation is performed by ASTROS' own database system (CADDDB). Steady aerodynamic analyses in ASTROS are performed by the USSAERO code, while the Doublet-Lattice and constant pressure methods are used for unsteady analyses in the subsonic and the supersonic regime, respectively.

The standard ASTROS solution sequence has been modified to allow a stop and restart of the optimization procedure after a certain number of iterations in order to allow the designer to review the design progress and to facilitate the call to the panel buckling analysis on the third level of the multilevel decomposition scheme (Fig. 1).

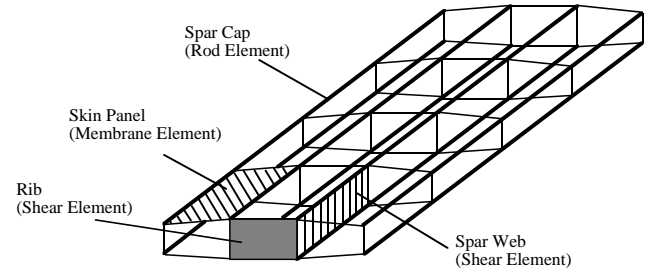


Fig. 2: Wing Box Finite Element Model

The wing structure is modeled consisting of spars, ribs, and skin panels. The skin panels are modeled as membrane elements, the spar webs and the ribs as shear panels, and the spar caps as rod elements (Fig. 2). All these elements can be designed, whereas posts that connect the upper and lower wing surface are modeled as rod elements that are not designed and mainly serve the purpose of preventing the global stiffness matrix from becoming ill-conditioned.

The number of designed elements for the HSCT wing ranges from a few hundred to around 1000, depending on the number of ribs and spars in the wing. Therefore, design variable linking schemes are necessary to reduce the number of design variables to a number that the optimizer can manage. ASTROS offers basically two ways of design variable linking, physical linking where the designed property of a selection of elements of the same type is set to one design variable, and shape function linking. In the case of shape function linking, the design variables are the coefficients of a polynomial, and the value of the polynomial at a certain location determines the value of the designed property of that specific element. In this case, a two-dimensional shape function of the form

$$t = a_{00} + a_{10}\xi + a_{01}\eta + a_{11}\xi\eta + a_{20}\xi^2 + a_{02}\eta^2 \quad (2)$$

is being used to model spar caps, webs, and skin panels, whereas the rib panels are physically linked to one design variable for each rib. One-dimensional shape function linking which proves beneficial especially when the number of spars is small can be achieved by setting the corresponding coefficients in the other direction to zero. The wing is subdivided into three design regions (Fig. 3), in each of which the design variable linking scheme can be selected individually.

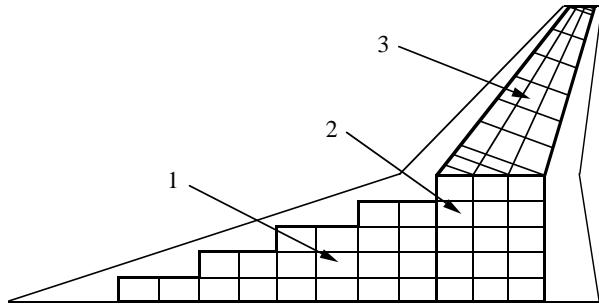


Fig. 3: Wing Design Regions

The component level of the three-level procedure optimizes selected wing skin panels for buckling. It uses the code PASCO (Panel Analysis and Sizing Code)^{11,12} developed by NASA Langley. PASCO was developed for the buckling and vibration analysis and sizing of prismatic structures having an arbitrary cross section. PASCO is primarily intended for analysis and sizing of stiffened panels made of laminated orthotropic materials. When used in the analysis mode, PASCO calculates laminate stiffnesses, laminate stresses and strains, buckling loads, vibration frequencies, and overall panel stiffness. When used in the sizing mode, PASCO adjusts sizing variables to provide a low-mass panel design that carries a set of specified loadings without exceeding buckling or material strength allowables.

2.1.2. Interfaces

A finite element pre-processor specifically designed for this problem has been written that takes the FLOPS wing geometry output and places a wing box into this geometry complete with all grid points, elements, element connectivity, static airloads, and design variable definition and linking scheme. The pre-processor creates the

complete ASTROS input file with the help of a small core file that mainly contains the ASTROS solution control commands. The user selects how he wants to model the wing structure (number of ribs, spars, design variable linking, number of different wing sections, initial and minimum values for the design variables) as described above. The fuel weight determined in FLOPS is distributed as point masses onto the inboard grid points for vibration and flutter analysis. The engine attachment to the wing structure is modeled by connecting rod elements that automatically connect the engines to the lower surface grid points closest to the spanwise engine locations in FLOPS. For static analyses, each engine is modeled by two point forces on the attachment structure, and for dynamic analyses, the engine masses are modeled as rods containing non-structural mass distributed along their length. Since the engine weights and locations are the actual values taken from the FLOPS file, the influence of engine placement on wing dynamic and aeroelastic behavior can be investigated.

The PASCO pre-processor accesses the ASTROS database and reads the information necessary to model user-selected skin panels, i.e. panel geometry, shape function design variable values, material constants and allowables. Out of this information a PASCO input file is automatically created that models the membrane element from ASTROS as a uniaxially stiffened panel. Different stiffener types are possible (blade, hat, Z, T, etc.).

The PASCO post-processor takes the load at which the individual optimized skin panel starts to buckle, together with its derivatives with respect to the design variables and places these values into the ASTROS database as the basis to formulate the ASTROS buckling constraint and its sensitivities to be used for the next ASTROS iteration.

Overall program execution control is being performed by UNIX shell scripts. A shell script calls the different codes in the right order and stops the execution at user-specified points so that the user can watch the flow of the optimization and change parameters if he so desires. Additionally, shell scripts perform all data filtering tasks necessary for the communication between the different analysis codes.

2.2 Aerodynamic Optimization

The aerodynamic optimization procedure uses both internal capabilities of FLOPS and the collection of computer codes compiled by Boeing called BDAP (Boeing Design and Analysis Program)¹³. FLOPS is equipped with the capability to read in aerodynamic tables and to scale the aerodynamic data as the geometry changes during the optimization. In this fashion higher-fidelity data can be used during the FLOPS optimization which would not be possible with the empirical aerodynamic capability that FLOPS is also equipped with. Move limits are imposed on the geometric parameters to ensure that the linear scaling used produces useful results. When the geometric parameters reach their limits, FLOPS has to be stopped and a new aerodynamic analysis with BDAP has to be performed.

2.2.1 BDAP - The Boeing Design and Analysis Program

The Boeing Design and Analysis Program is a collection of eight individual computer programs for the aerodynamic design and analysis of supersonic configurations. All programs use a standard input and output format and make use of the same graphic routines. The individual programs calculate skin friction drag using turbulent flat plate theory, wave drag both with far-field and with near-field methods, lifting pressures, drag-due-to-lift and pitching moment and trim drag.

In the analysis mode, the force coefficients of a given configuration are built up through superposition (Fig. 4). In the design mode, the program produces a minimum drag configuration of the current planform and exterior geometry through twist and camber optimization of the wing and wave drag minimization through area ruling of the wing-nacelle-fuselage-tail configuration. The wave drag minimization through area ruling uses the far-field wave drag model developed by Harris¹⁴.

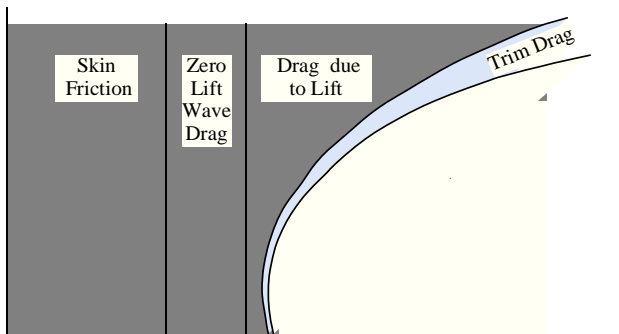


Fig. 4: Drag Buildup in BDAP

The near-field wave drag model is used to calculate zero-lift thickness pressure distributions on the entire wing-body-nacelle-empennage configuration. It employs the same Mach box approach that is used for the lifting-pressure and drag-due-to-lift calculations.

The determination of drag-due-to-lift and c_p -distribution is performed by WINGDES¹⁵ which is part of the BDAP system. WINGDES generates an optimized twisted and cambered lifting surface for a given wing planform operating at specified flight conditions, provides the corresponding lifting pressure distribution, and gives wing force and moment data. The code provides an analysis of the designed surface and may be operated in an analysis-only mode. Supersonic and subsonic speeds can be handled, but it is not a transonic code. Because the solution is based on the use of candidate surfaces, it can provide a twisted and cambered surface restricted to specified wing regions (mission adaptive design) as well as whole-wing design.

The numerical method is based on linearized theory potential flow solutions for a zero-thickness lifting surface represented by an array of horseshoe vortices. A solution by iteration rather than by a matrix inversion is used. The code also provides for an estimate of attainable leading edge thrust and of the forces caused by separated leading edge vortices. Attainable leading edge thrust considerations play a direct part in the design process, but

vortex force estimates do not except for a reduction of the design lift coefficient (and camber) caused by the vortex lift contribution.

2.3 Combined Aerodynamic and Structural Optimization Procedure

A procedure has been developed that links the multilevel structural optimization described in 2.1 with the aerodynamic optimization described above. The goal is the determination of the so-called "jig" shape, i.e. the shape of the undeformed wing that is necessary so that the wing deforms into its optimum shape in the cruise condition as it was determined in the aerodynamic optimization. At the same time, the wing whose undeformed shape is not yet known is designed for its design load cases in an iterative procedure. The airloads on the deformed structure are generated within ASTROS for the time being, but it is envisioned that higher-fidelity codes will be used later on to produce more accurate airloads for the deformed structure.

The procedure to determine the wing jig shape is executed according to the flow chart in figure 5. In the flowchart, only the main design codes are displayed. The arrows between the boxes with the codes can be assumed to represent the interfaces. Initially FLOPS produces a converged design point which is called baseline configuration. For the wing planform and cruise condition of this design WINGDES is run to determine the optimum twist and camber distribution. This twist and camber distribution is superimposed over the "flat" wing grid that the ASTROS pre-processor has produced. This gives us the final cruise shape into which the wing is supposed to deform. The wing structural design with ASTROS is started from this point and stopped after four to five iterations - before convergence is reached. At this point the wing deflection under the cruise load is determined and subtracted from the initial shape. ASTROS is then started again from exactly the point where it was stopped - the current values of the global design variables are stored and used as the new starting point. The procedure turns out to be highly convergent - due to the linearity of the structural behavior and the aerodynamic model that is currently used. This way one additional update of the initial finite element grid after another approximately three iterations produces almost exactly the desired cruise shape under the cruise load. The unloaded FE model then corresponds to the undeformed wing jig shape.

In the full procedure with an optimization at the system level performed in FLOPS, an iteration is performed through the flowchart in Fig. 5 until overall convergence is reached. The final result is a wing that is designed for any number of static and dynamic load cases and that deforms into its optimum shape for the level 1-g cruise flight and an aircraft capable of flying the prescribed mission with a maximum productivity index. The procedure as such is not in any way dependent on the tools that are currently employed - both on the aerodynamic and on the structural side. All codes are run as stand-alone programs, and all scheduling, communications, and data filtering tasks are performed by UNIX shells and small interface and interpolation programs.

A higher-fidelity aerodynamic model may worsen the convergence behavior eventually, but under a 1-g cruise flight the deflections are not extremely large so that a linear approach for the aerodynamics most likely does not produce large errors.

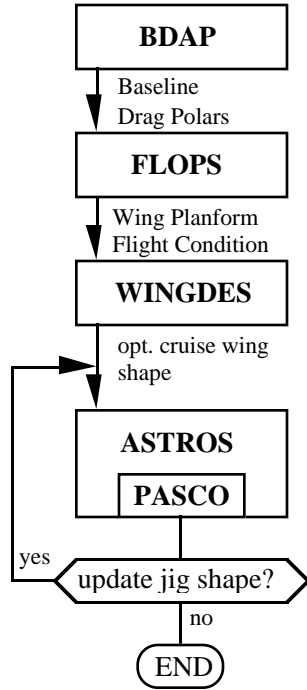


Fig. 5: Flowchart for the Jig Shape Determination

3. HSCT Baseline Configuration and Models

In order to be able to analyze different HSCT wing configurations, a baseline High-Speed Civil Transport was defined. Due to the availability of information at the time the baseline aircraft was established, the NASA HiSAIR project was the main source of the Georgia Tech baseline HSCT. The configuration used here is closest to the NASA HiSAIR configuration of 1992^{16,17} with a range of 6500 Nm, 250 passengers and a wing area of 9000 ft². A FLOPS input file was compiled for this configuration. With this input, a FLOPS run was performed in order to produce a converged design capable of flying the prescribed mission. FLOPS produced a configuration with a TOGW results at 703974 lb, with a fuel weight of 401200 lb and a productivity index of 100.08 Kts. Table 1 further describes the main characteristics of the resulting aircraft.

The 9000 ft² wing thus obtained (Fig. 6) has an aspect ratio of 2.678 and a leading edge sweep of 73° inboard and 43° outboard. The resulting wing span is 155.25 ft. Information about the wing thickness and airfoil was not available, so a 3% thick airfoil was assumed, and for all the latest configurations analyzed an actual NACA 62003 airfoil was used as an envelope for the wing box.

The baseline mission specified for the calculations consists of 10 min taxi and warm-up, take-off at sea level, standard day, climb out at 250 Kts TAS, accelerating climb to the initial cruise altitude of 56000 ft, then a supersonic cruise at Mach 2.4 and optimum altitude for maximum

specific range to the destination. After descent, landing and taxi for 5 min, standard reserves for a flight for 250 Nm to an alternate airport at 10000 ft and a holding time of 30 min are taken into account (see Fig. 7). This is a simplified mission that is just being used to establish the methodology. There is no doubt that a real HSCT mission will have to include a subsonic cruise part since supersonic cruise over populated areas will most likely not be possible due to sonic boom constraints.

Performance, General		
Passengers		250
Range	[Nm]	6500
Cruise Mach No.		2.4
Max. Cruise Altitude	[ft]	70000
Productivity Index	[Kts]	100.08
Engine Type		Turbine-Bypass
Net Thrust (SLS)	[lb]	50000
Number of Engines		4
Geometric Data		
Fuselage Length	[ft]	300.0
Wing Span	[ft]	155.25
Wing Area	[ft ²]	9000.0
Aspect Ratio		2.678
Leading Edge Sweep, Inboard	[deg.]	73.0
Leading Edge Sweep, Outboard	[deg.]	43.0
Wing Thickness to Chord Ratio	[%]	3.0
Weights		
Wing	[lb]	83251.
Fuselage	[lb]	39971.
Total Structure	[lb]	142189.
Propulsion	[lb]	57896.
Systems and Equipment	[lb]	40273.
Empty Weight	[lb]	240357.
Operating Items	[lb]	7622.
Operating Empty Weight	[lb]	247979.
Passengers	[lb]	41250.
Baggage, Cargo	[lb]	13545.
Zero Fuel Weight	[lb]	302774.
Mission Fuel	[lb]	401200.
Take Off Gross Weight	[lb]	703974.

Table 1: Main Characteristics of the HSCT Baseline Configuration

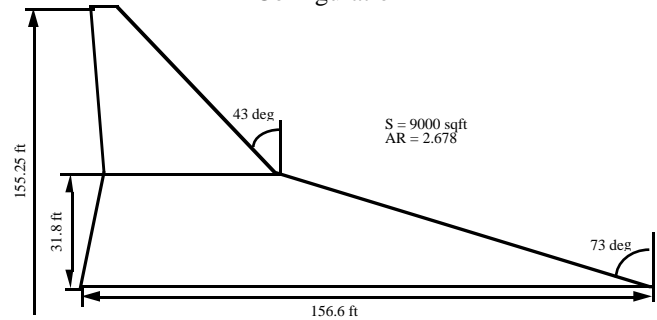


Fig. 6: HSCT Baseline Wing

Wing Finite Element and Aerodynamic Models

The ASTROS finite element model of the HSCT baseline wing consists of four main spars and five ribs in the inboard and seven in the outboard section. Skins are modeled as membrane elements, spar webs and ribs as shear

panels, and spar caps and posts as rod elements, see Figure 8. The fuselage is represented by a stick model of beam elements containing non-structural mass to account for payload and systems. The engines are modeled as mass-containing rod elements that are attached to the wing box via connecting rods. Both a free-free boundary condition and a clamped boundary condition have been defined, where the first is used for the aeroelastic and steady aerodynamic analyses, the latter for static analyses.

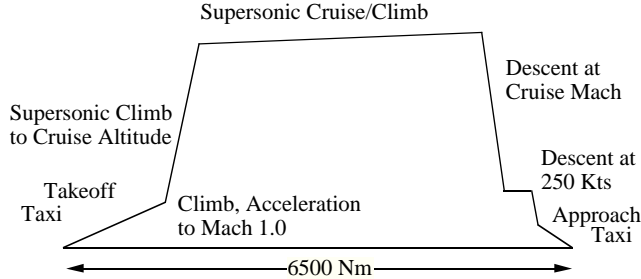


Fig. 7: Mission Profile

The four-spar-model consists of 569 elements, out of which 421 are designed, linked to 51 to 62 design variables. 62 design variables are used for the buckling optimizations, where only the top skin panels are buckling critical. In the other cases top and bottom skin panels are linked to the same design variables.

Both a steady and an unsteady aerodynamic panel model of the HSCT wing have been defined in ASTROS. The steady model consists of two wing sections with 30 panels inboard and 100 panels outboard (Figure 9). The unsteady model consists of an inboard and an outboard macro element with 45 panels inboard and 80 panels outboard.

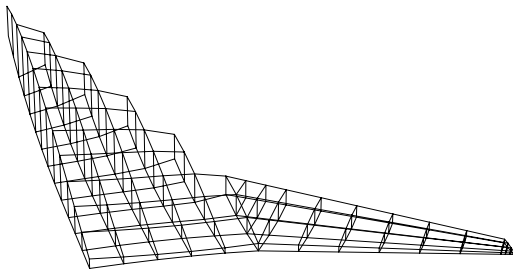


Fig. 8: 4-Spar Finite Element Model

Load Cases

ASTROS allows the definition of basically an unlimited number of load cases. In the trial runs for the verification of the ASTROS - buckling integration, three load cases have been selected that appeared critical for the Lockheed SST configuration studies of the 70s¹⁸, two static 2.5 g pull-up conditions, and a subsonic flutter case

at low altitude. Table 2 shows the details of the three load cases.

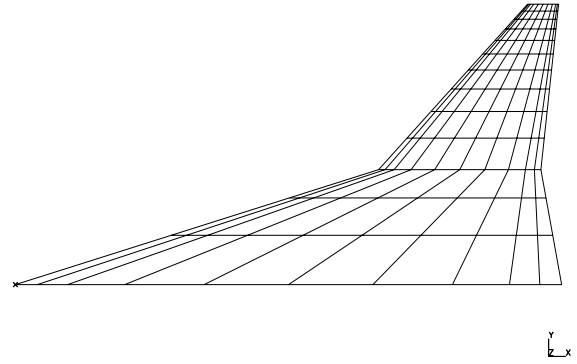


Fig. 9: Steady Aerodynamic Panel Model

Load Case	Load Factor	Mach No.	Altitude [ft]	dyn.press. [lb/sqft]	Weight [lb]
1, FFFP	2.5	2.4	60000	603.93	662166
2, EFPF	2.5	2.4	60000	603.93	305225
3, Flut.	-	0.8	0	948.07	662166

Table 2: Design Load Cases

Materials

Although all the codes employed and the overall optimization procedure are capable of and also meant to optimize composite structures, for the sake of simplicity two metals have been used for testing the procedure. One wing configuration is completely made up of titanium (Ti6Al4V, designated "ti"), whereas the other one has an "advanced aluminum"¹⁷ substructure (spars, ribs, posts) and titanium skin panels. The material data are shown in table 3. A safety factor of 1.2 with respect to the material yield limits has been used in all static load conditions.

Material	Adv. Aluminum	Ti6Al4V
E [10 ⁶ psi]	12.0	16.0
ν	0.318	0.290
ρ	0.105	0.160
$\sigma_x \sigma_y$ [psi] yield	61500	86700
σ_{xy} [psi] yield	23300	50700
ϵ_x, ϵ_y	0.00513	0.00542
ϵ_{xy}	0.00482	0.00817

Table 3: Material Data

4. Results

Various analyses have been performed with different material configurations and structural concepts, the results of which all show similar tendencies. Due to space limitations, only the results for one material configuration are shown here, titanium skin panels and aluminum substructure in a four-spar configuration.

Fig. 10 shows the convergence behavior of the ASTROS runs where the two locations are indicated where the undeformed structure has been updated. For all cases considered, convergence behavior has been similarly smooth. The resulting wing structural weight for one wing for this load case is 17462 lb without considering skin panel buckling (called "stfl") and 19081 lb for the buckling case ("stflb"). Table 4 shows the weight distribution onto the different structural components. In general, consideration of skin panel buckling for the top skin panels adds between 1500 and 2000 lb to the structural weight for this spar / rib layout, as it has been shown in previous studies⁷. The weight breakdown shows that for the buckling case material is shifted from the spar webs and

especially the spar caps to the skin panels as it is needed there to prevent buckling. The ribs are completely unaffected by the buckling consideration - as it was to be expected.

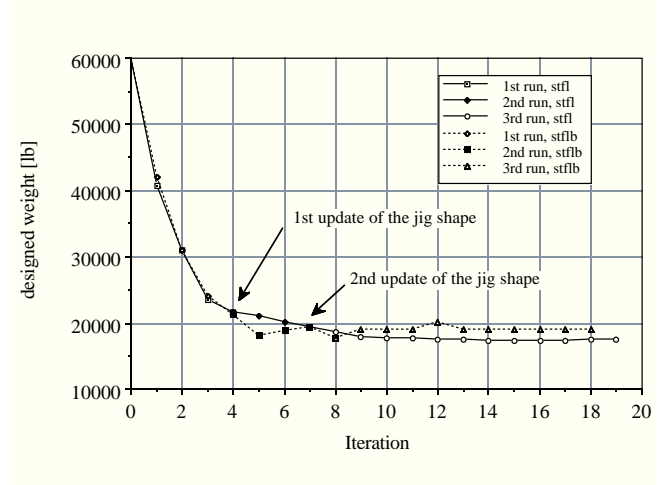


Fig. 10: ASTROS Convergence History

Case	skin panels	spar webs	spar caps	ribs	total designed weight
stfl	12037.99	1160.99	332.79	3929.86	17461.64
stflb	13984.06	1009.55	160.37	3927.02	19081.00

Table 4: Weight Breakdown of the Optimized Wings [lb] (for one wing)

The resulting skin panel thicknesses can be seen in Fig. 11, 12, and 13. Fig. 11 shows both the top and bottom thicknesses which are the same due to the design variable linking scheme, whereas top and bottom skins are different for the buckling case where only the top skins are buckling critical. Thicknesses range from minimum gage (0.01 inches) in the unloaded tip and strake areas to 0.25 inches in the wing break section without considering buckling (Fig. 11) and to 0.34 inches for the top skin panels designed for buckling (Fig. 13). The thickness distribution of the bottom skin panels for the buckling case is very similar to the case not designed for buckling.

Fig. 14 to 16 show the corresponding von Mises' stress distributions which are used as the static failure

criterion. Fig. 14 shows the high stress levels of the whole wing center section in the case where buckling is not considered. In this case the von Mises' stress is the critical design driver except for the inboard trailing edge that is thicker than the static load would require. Here the flutter case comes into play that requires the torsional rigidity to be increased. The stress level of the bottom panels for the buckling case (Fig. 16) are again very similar to the ones without buckling constraints. As it was to be expected, stress levels for the buckling critical wing center section of the top skin (Fig. 15) are considerably lower than for the two other ones. Here buckling is clearly the design driver.



Fig. 11: Skin Panel Thicknesses, stfl



Fig. 12: Top Skin Panel Thicknesses, stflb



Fig. 13: Bottom Skin Panel Thicknesses, stflb

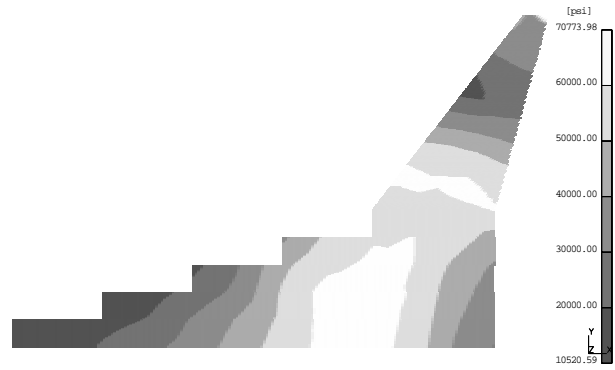


Fig. 16: Bottom Skin Panel Stresses, stflb



Fig. 14: Skin Panel Stresses, stfl

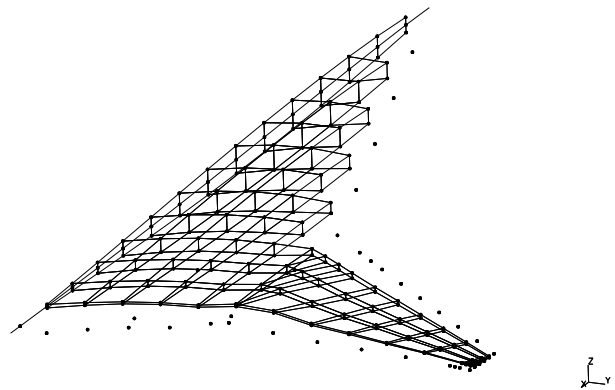


Fig 17: Optimum Cruise Shape



Fig. 15: Top Skin Panel Stresses, stflb

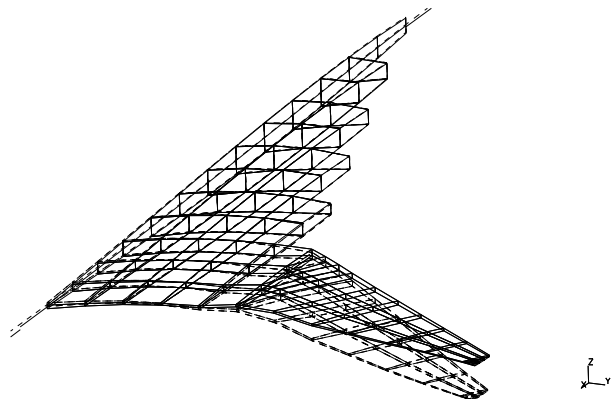


Fig 18: Static Displacements, 1 g, stflb

Fig. 17 shows the optimum cruise shape as it was determined by WINGDES for this planform. In Fig. 18 the resulting undeformed (jig) shape for the buckling case is displayed in dashed lines with the actual deflection for the 1-g cruise condition determined by ASTROS superimposed. The wing tip deflects by 68 inches at the trailing edge and 67 inches at the leading edge. The deviation of the actual shape under the 1-g load from the

desired shape is so small that it is not noticeable on a drawing this scale (Fig. 19) - the maximum difference is about 1 inch in the tip region, compared to a half-span of 931.5 inches. Fig. 20 finally shows the wing deflection under the 2.5 g static design load with full fuel tanks - about 170 inches at the wing tip. A modal analysis of the free-free model was performed with the resulting mode shapes for the first five modes displayed in Fig. 21. The

first mode consists mainly of fuselage bending with a frequency of 1.17 Hz, which may not be accurate due to the fuselage representation as a simple beam. Mode 2, the first wing bending mode, results at 1.35 Hz, and the first torsional mode at 2.24 Hz. Mode 4 is mainly 2nd wing bending, whereas mode 5 shows the plate behavior of the wing at 3.48 Hz. All these results are shown for the buckling case only since the results for the case not considering buckling are almost identical and would not give any new insights.

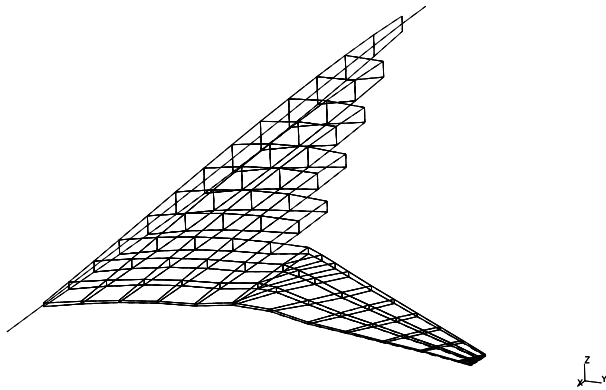


Fig 19: Desired and Actually Achieved Cruise Shape

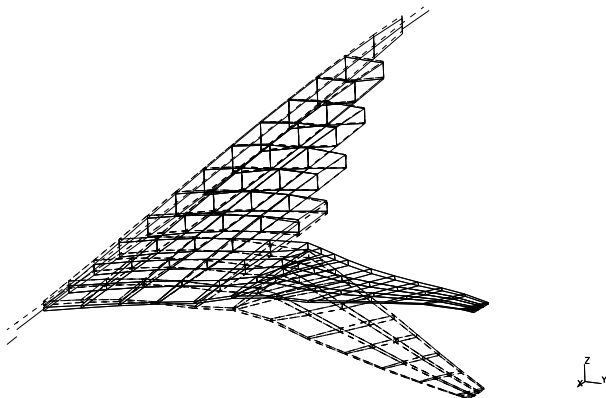
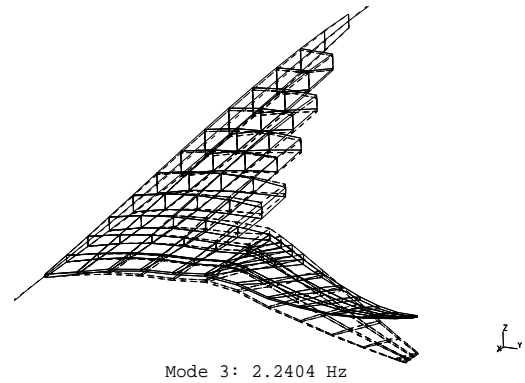
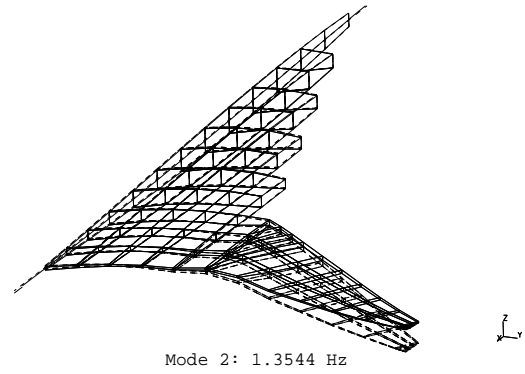


Fig 20: Static Displacements, 2.5 g, stflb

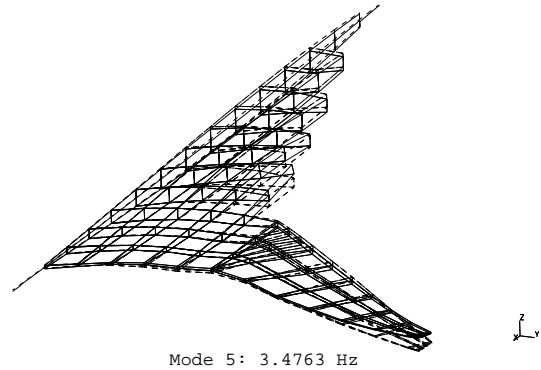
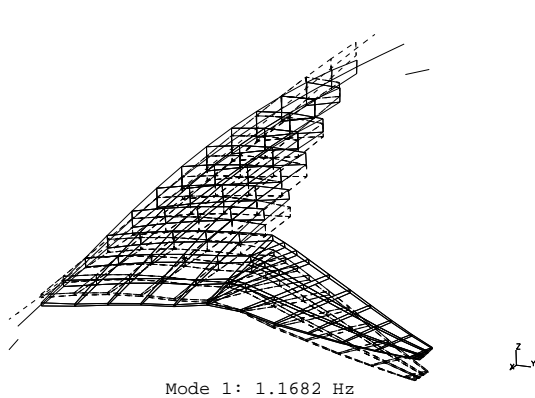
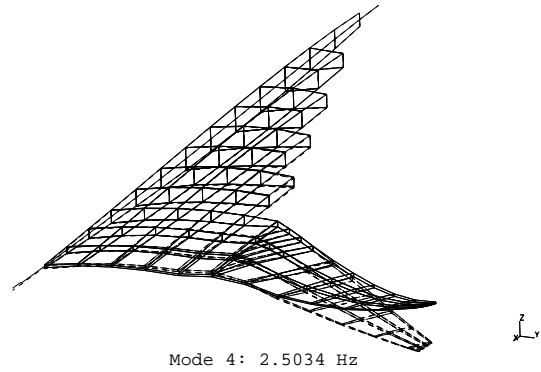


Fig. 21: Mode Shapes of the Optimized Wing

5. Conclusions

A simple and efficient procedure has been presented that determines the undeformed wing shape so that the wing deforms into its optimum cruise shape under the cruise load condition. The procedure is integrated into a multidisciplinary wing design environment which combines structural and aerodynamic wing design. The procedure is applied to the design of an HSCT configuration as a focal point of the current research at the Georgia Tech ASDL, but it is applicable to any kind of aircraft. The procedure is extremely flexible due to its modular structure and the application of stand-alone codes that can easily be substituted. Data filtering and overall execution is performed by UNIX shell scripts which has proven to be very beneficial for the modular structure. With the current aerodynamic and structural design tools the procedure is highly convergent and results in a deformed wing shape almost exactly equal to the desired shape. At the moment the procedure may be slightly biased towards the structural side in terms of effort and fidelity, but the modular approach provides for an easy substitution of WINGDES by any other aerodynamic design program. The only information that is required is a desired wing shape in terms of deflections at a known number of chordwise and spanwise points.

Thus the procedure provides the missing link between the aerodynamic and structural optimization procedures currently being developed at the ASDL. All these developments must be seen in the larger perspective of multidisciplinary design optimization techniques focusing on the HSCT which integrate structures, aerodynamics, propulsion, and controls that the ASDL has been heavily involved in for a number of years.

6. References

- [1] FLOPS User's Guide, Release 5.0, NASA Langley Research Center, November, 1992
- [2] ACSYNT Manual and User Guide, Version 2.0, ACSYNT Institute, Blacksburg, VA, January, 1993
- [3] Sobieszczanski-Sobieski, J.: Sensitivity Analysis and Multidisciplinary Optimization for Aircraft Design: Recent Advances and Results, Journal of Aircraft Vol.27, No. 12, December 1990
- [4] Schrage, D.P.; Rogan, J.E.: The Impact of Concurrent Engineering on Aerospace Systems Design, 1991
- [5] Schrage, D.P.: Introduction to Concurrent Engineering, Class Notes, Fall 1992
- [6] Mavris, D.N., Schrage, D.P.: Integrated Design and Manufacturing for the High-Speed Civil Transport, AIAA 93-3994, AIAA/AHS Design, Systems, and Operations Meeting, Monterey, CA, August 1993
- [7] Röhl, P.J.; Schrage, D.P.: Multidisciplinary Wing Design of a High Speed Civil Transport Aircraft by Multilevel Decomposition Techniques, AIAA 92-4721, 4th AIAA/Air Force/NASA Symposium on Multidisciplinary Analysis and Optimization, Cleveland, OH, September 1992
- [8] Röhl, P.J.; Mavris, D.N., Schrage, D.P.: A Multilevel Wing Design Procedure Centered on the ASTROS Structural Optimization System, AIAA 94-4411, 5th AIAA/Air Force/NASA Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September 1994
- [9] Röhl, P.J.; Mavris, D.N., Schrage, D.P.: A Multilevel Decomposition Procedure for the Preliminary Wing Design of a High-Speed Civil Transport Aircraft, First Industry / University Symposium on Supersonic Transport Vehicles, North Carolina A&T State University, Greensboro, NC, December 1994
- [10] ASTROS Version 10 User Manuals, Universal Analytics, Inc., Torrance, CA, March 1993
- [11] Anderson, M.S.; Stroud: PASCO Structural Panel Analysis and Sizing Code, Capability and Analytical Foundations, NASA Langley Research Center, NASA-TM 80181, November 1981
- [12] Anderson, M.S.; Stroud, W.J. et al.: PASCO Structural Panel Analysis and Sizing Code, User's Manual, NASA Langley Research Center, NASA-TM 80182, November 1981
- [13] Middleton, W.D.; Lundry, J.L.: A System for Aerodynamic Design and Analysis of Supersonic Aircraft, NASA CR 3351, Boeing Commercial Airplane Company, Seattle, WA, 1980
- [14] Harris, R.V.Jr.: An Analysis and Correlation of Aircraft Wave Drag, NASA TM X-947, 1964
- [15] Carlson, H.W.; Walkley, K.B.: Numerical Methods and a Computer Program for Subsonic and Supersonic Aerodynamic Design and Analysis of Wings with Attainable Thrust Considerations, NASA CR-3808, 1984
- [16] Coen, P.G.; Sobieszczanski-Sobieski, J.; Dollyhigh, S.M.: Preliminary Results from the High Speed Airframe Integration Research, AIAA Paper 92-1004, 1992
- [17] Barthelemy, J.-F. M.; Wrenn, G.A, et al.: Integrating Aerodynamics and Structures in the Minimum Weight Design of a Supersonic Transport Wing, AIAA Paper 92-2372, April 1992
- [18] Sakata, I.F.; Davis, G.W.: Substantiating Data for Arrow-Wing Supersonic Cruise Aircraft Structural Design Concepts Evaluation, Vol. 1-4, NASA CR-132575, Lockheed California, 1976